SAND2018-6588C

Application of the Sandia Array Performance Model to Assess Multiyear Performance of Fielded CIGS PV Arrays

Bruce H. King, Charles D. Robinson, Craig Carmignani, Daniel Riley and C. Birk Jones

Sandia National Laboratories, Albuquerque, NM, 87185-0951, USA

Abstract — Copper indium gallium (di)selenide (CIGS) photovoltaic cell technology has long been promoted as a cost-effective alternative to traditional PV modules based on crystalline silicon cells. However, adoption of CIGS is hindered by significant uncertainties regarding long-term reliability and performance stability, as well as a lack of accurate modeling tools to predict CIGS system performance. Sandia is conducting a multi-year study of fielded CIGS systems that range in age from 3-6 years and represent a cross-section of commercial manufacturing and packaging. Most of these arrays include modules that were thoroughly characterized prior to deployment. In this paper, we explore uncertainty in the long-term reliability and performance stability of CIGS modules by analyzing real world performance and degradation rates of these systems.

***Index Terms* — CIGS, outdoor testing, degradation assessment, Sandia Array Performance Model, SAPM.**

I. Introduction

Copper indium gallium (di)selenide (CIGS) photovoltaic cell technology has long been promoted as a cost-effective alternative to traditional PV modules based on crystalline silicon cells. Recent improvements in CIGS cell efficiency have demonstrated the potential to challenge crystalline silicon modules on the basis of power density as well [1]. However, adoption of CIGS is hindered by significant uncertainties regarding long-term reliability and performance stability. Further, there is a considerable gap between fundamental cell studies and a comprehensive understanding of field performance [2].

TABLE I
Systems Under Study at Sandia

System	Cell	Package	Size (kW)	Installed
CIGS-1	discrete	polymer/flex	3.36	1/12
CIGS-2	discrete	glass-glass	2.2	1/12
CIGS-3	discrete	glass-glass	2.32	6/12
CIGS-4	monolithic	glass-glass	4.8	6/13
CIGS-5	monolithic	glass-glass	6	4/15
CIGS-6	monolithic	glass-glass	6	4/15

To address these gaps in knowledge, Sandia is conducting a multi-year study of fielded CIGS systems. The systems in this study range in age from 3-6 years (Table 1) and represent a cross-section of commercial manufacturing and packaging methods. Each system is instrumented to measure DC voltage and current while reference irradiance is measured using local broadband global pyranometers in the plane of array. Detailed electrical performance characterization of individual modules were made prior to installation and these same modules have been recharacterized periodically to track stability.

In 2017, we presented the initial results from this study [3]. Half of the systems displayed significant annual degradation in P_{mp} of ~2%/year or greater, while the other half displayed little to no degradation. No correlation was observed between degradation (or stability) and cell type or module construction. Systems CIGS-1 displayed visible package degradation while CIGS-4 displayed multiple module failures. These systems were decommissioned.

In this paper, we present updates to the module degradation assessment including recent recharacterization data from 2018. The focus of this paper will be on systems CIG-2,3 and 6, since systems CIGS-1 and 4 have been retired from the study. Additionally, Systems CIGS-5 and 6 are very similar. Monitored data from each system is analyzed and compared against predicted performance from the Sandia Array Performance Model [4]. These results are used to assess system degradation rate and compared to measurements from individual module characterization. An assessment of the validity of using SAPM to track system degradation for each module type is then made. Seasonal variations in system performance are also discussed.

Fig. 1. Two CIGS arrays under test at Sandia

II. Experimental Procedure

A. System Instrumentation

Each system is instrumented to measure DC voltage and current using calibrated commercial current shunts and custom voltage dividers designed and produced by Sandia. Module temperature is monitored using type-T thermocouples adhered to the backside of selected modules. Reference irradiance is measured using local broadband global pyranometers (Kipp &

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Zonen CMP-11) in the plane of array. Local analog measurements are digitized using high accuracy A/D converters (ICPDAS). Data logging is via RS-485 communications using a variety of data loggers (Campbell Scientific CR1000 or CR6; Raspberry Pi). Time-series data is logged every five seconds, from which one-minute averages are produced. Additional data is obtained from a co-located weather platform including direct normal irradiance (DNI), global normal (GNI), wind speed, ambient temperature, humidity, barometric pressure and precipitation. All data acquisition systems are synchronized to a local time server. Data is quality checked using custom Python scripts [5] and transferred nightly into a remote database.

B. Module Characterization

Indoor flash testing was performed using a Spire 4600SLP. Modules were light soaked outdoors under natural sunlight prior to characterization. New modules characterized prior to installation were light soaked on a fixed tilt rack according to manufacturers' guidelines. Aged modules were removed from functioning arrays near solar noon on clear days and characterized within one hour of removal. In 2017, two groups of modules were additionally light soaked indoors according to IEC 61215-1-4 [6]. Comparison between these methods indicated that natural light soaking produced results comparable or slightly superior to artificial light soaking. Details of this study are beyond the scope of this paper and are not reported here.

C. Tracker testing for model calibration

Detailed performance measurements of individual modules were made outdoors using a two-axis Azimuth-Elevation solar tracker and measurement techniques developed at Sandia [7, 8]. Modules were instrumented with thermocouples attached to the back surface of the module and then mounted on the tracker. The majority of measurements are performed with the module held normal to the sun.

After an appropriate light-soaking period, IV curves are measured at two-minute intervals under clear and cloudy conditions across multiple days, typically two weeks or more to determine the module's response to changing irradiance, temperature and spectrum. Using newly developed methods [9], a simultaneous multivariate regression analysis is performed to solve for each component of the Sandia Array Performance Model, including temperature coefficients. This procedure differs from the traditional method of calibrating the SAPM in which a deterministic thermal test is performed. The initial step of the traditional methods requires the module to be fully shaded in order to cool to ambient temperature. This shading procedure may induce relaxation in CIGS [10], leading to a dynamic state when uncovered to determine temperature coefficients. The new procedure avoids this potential pitfall by using data measured in a quasi-steady state.

Finally, the angle of incidence behavior of the module is determined by measuring short circuit current at prescribed incident angles between the sun and the module normal. The combined set of SAPM coefficients for each module type are then used for predictive system performance modeling.

III. System Performance Modeling

System performance was modeled using novel methods of applying the Sandia Array Performance Model (SAPM) [4] to time series data. SAPM relies on model coefficients derived from outdoor characterization of individual modules on a two-axis tracker (Section II. B). Inputs are local weather and irradiance.

It is common practice to utilize local reference cells in the plane of array for system time-series analysis. For reference cells that are well-matched to the array, this has an advantage in that there is no need to apply spectral or angle of incidence corrections. However, this type of reference device introduces inaccuracy when used to analyze system data for thin film technologies such as CIGS, primarily due to spectral mismatch between the array and reference device. Moreover, SAPM includes a built in spectral correction function ($f_1(Ama)$) that is calibrated to broadband irradiance measured with a global pyranometer. The use of a broadband global pyranometer introduces the need to adjust measured irradiance to correct for solar angle of incidence on the plane of array. But again, SAPM includes a build-it in correction ($f_2(AOI)$) that is calibrated to broadband irradiance measured with a global pyranometer.

Net irradiance reaching the cells, accounting for reflection losses may then be found from

$$E_{net} = E_{POA} - E_{DNI}\cos(AOI)[1 - f_2(AOI)]$$

and effective irradiance accounting for spectral mismatch may be found from

$$E_e = f_1(AM)E_{net}$$

Using the wind speed and module-to-cell temperature models from SAPM, effective cell temperature may be found from

$$T_c = E_{net}\,[e^{a+b*WS}] + \frac{E_{net}}{1000}\,\Delta T + T_a$$

Finally, current and voltage at maximum power may be found from

$$I_{mp} = I_{mpo}[C_0E_e + C_1E_e^2]\left[1 + \hat{\alpha}_{Imp}[T_c - T_0]\right]$$

$$V_{mp} = V_{mpo} + C_2N_s\delta(T_c)\ln(E_e) + C_3N_s[\delta(T_c)\ln(E_e)]^2 + \beta_{Vmp}[T_c - T_0]$$

and maximum power is simply the product of these two.

$$P_{mp} = I_{mp}V_{mp}$$

This procedure is applied to each measured data point, time synchronized to measured local weather data. An example daily power profile for a clear day is shown in Figure 2.

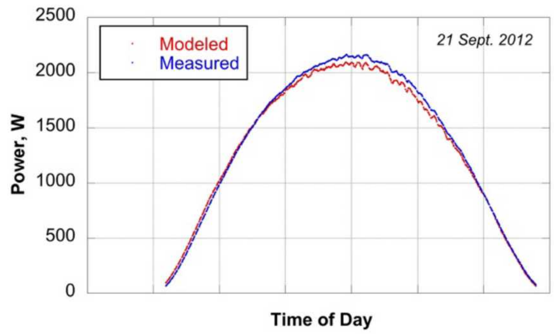

Fig. 2. Measured vs Modeled daily power profile for CIGS-3

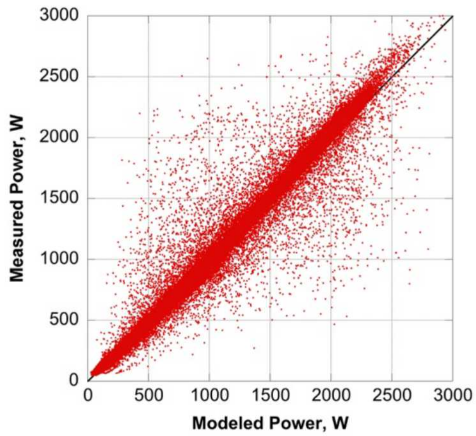

Fig. 3. Measured vs Modeled power for CIGS-3 for each time step. All sky conditions are represented (2012).

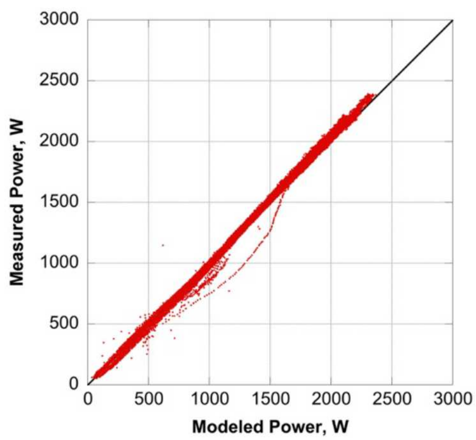

Fig. 4. Filtered Clear Sky Measured vs Modeled power for CIGS-3 for each time step (2012).

Example results for one system, CIGS-3, are shown in Figures 3 and 4. These results are for a single year, 2012. Figure 3 displays results for every data point collected during this time period. In general, the correlation between measured and modeled results is very good. A low mean bias error of -10.5W is found for the time series, despite the visual appearance of considerable scatter.

Additional analysis may be performed to remove cloudy conditions. Here, a clear sky detection algorithm [11, 12] is used to identify clear data points using local global horizontal irradiance measurements from the local weather station. These are then used to identify individual days when variability in irradiance is low during the period from 9am to 3pm. Once these days have been identified, the corresponding measured data and performance model can easily be isolated from the all-sky data set. An example is shown in Figure 4, where this filter has been applied to the data set shown in Figure 3.

Finally, time series measured data and model predictions for each time step were aggregated into daily cumulative totals and daily measured/modeled ratios were calculated, consistent with Power Performance Index (PPI) detailed in [13]. A similar approach was applied to measured current and voltage.

$$PPI = \frac{\sum_k (Measured\ Power)_k (time)_k}{\sum_k (Predicted\ Power)_k (time)_k}$$

IV. Results and Discussion

A. Flash Test STC Results

Flash test results are presented in Table II. Modules from system CIGS-2 displayed significant decrease in power (-14.9%), continuing a downward trend observed in 2017. CIGS-3 also continued a trend of stability observed in 2017. In 2017 CIGS-6 was also observed to be stable. However, in 2018 it was seen to have degraded significantly. Changes in power were not correlated with cell type/module construction. The decrease in power was reflected in a decrease in fill factor for both CIGS-2 and 6, whereas fill factor was stable for CIGS-3.

For CIGS-2, the reduction in power continued to be correlated with a decrease in I_{mp} and a smaller drop in V_{mp}. This trend was further reflected in a continued decrease in shunt resistance (R@Isc).

IV. Results and Discussion

A. Flash Test STC Results

Flash test results are presented in Table II. Modules from system CIGS-2 displayed significant decrease in power (-14.9%), continuing a downward trend observed in 2017. CIGS-3 also continued a trend of stability observed in 2017. In 2017 CIGS-6 was also observed to be stable. However, in 2018 it was seen to have degraded significantly. Changes in power were not correlated with cell type/module construction. The decrease in power was reflected in a decrease in fill factor for both CIGS-2 and 6, whereas fill factor was stable for CIGS-3.

For CIGS-2, the reduction in power continued to be correlated with a decrease in I_{mp} and a smaller drop in V_{mp}. This

TABLE II
AVERAGE MODULE STC PERFORMANCE DETERMINED FROM FLASH TESTING

System ID	**CIGS-2**				**CIGS-3**				**CIGS-6**			
# Modules	1				2				5			
Age, months	0	45	76	%Δ Total	0	41	70	%Δ Total	0	23	38	%Δ Total
P_{mp} (mW/cm²)	12.0	11.1	10.2	-14.9%	13.5	13.7	13.7	1.6%	12.9	13.0	12.1	-5.7%
I_{sc} (mA/cm²)	30.1	29.9	30.3	0.8%	29.2	29.8	30.2	3.6%	31.3	30.7	30.6	-2.4%
V_{oc} (mV/cell)	595	581	572	-3.8%	639	639	637	-0.3%	591	597	593	0.4%
I_{mp} (mA/cm²)	26.0	24.3	23.2	-10.8%	26.0	26.4	26.6	2.4%	27.9	27.7	27.2	-2.3%
V_{mp} (mV/cell)	464	458	442	-4.6%	519	518	515	-0.8%	461	468	445	-3.5%
R@I_{sc} (Ω-cm²)	326	210	143	-56.3%	423	465	423	0.0%	-	1116	878	-
R@V_{oc} (Ω-cm²)	2.65	2.19	2.54	-4.2%	0.94	1.90	2.01	113.9%	-	2.74	4.13	-
Fill Factor	0.67	0.64	0.59	-12.2%	0.72	0.72	0.71	-1.5%	0.69	0.71	0.67	-3.7%

trend was further reflected in a continued decrease in shunt resistance (R@Isc).

Results from CIGS-3 were largely unremarkable other than to note the lack of significant degradation in flash test results for this system.

In contrast, CIGS-6 which had shown only minor degradation in 2017 showed a significant drop in power in 2018. I_{sc} and V_{oc} were observed to be stable year-over-year, but both I_{mp} and V_{mp} were observed to drop. These changes were accompanied by both a decrease in shunt resistance and an increase in series resistance.

A summary of the annual rate of change in Pmp at STC for each of the modules is shown below in Table IV.

TABLE III
ANNUAL RATE OF CHANGE IN PMP AT STC

System	**2016-2017**		**2018**	
	Age	%Δ	Age	%Δ
CIGS-2	45	-2.0%	76	-2.4%
CIGS-3	41	0.4%	70	0.3%
CIGS-6	23	0.4%	38	-1.8%

B. Measured and Modeled System Results

Measured and modeled system results are shown in Figures 5-7. Significant gaps in monitored system data are apparent for systems CIGS-2 and 3 between 2013-14 and 2016. While the data monitoring systems were off-line during this time, the systems were operational and grid-tied. CIGS-2 additionally experienced a current transducer failure between 2016 and 2017. While much of the data collected during this time is believable, it is not known when the transducer failed. This data was therefore excluded from analysis. Measured voltage data during this time was good and is retained in the analysis.

Measured/modeled results generally confirm the general trends observed from flash testing (Table IV). A pronounced drop in power, current and voltage can be seen for CIGS-2, while CIGS-3 is relatively stable. Each system displays seasonal behavior relative to the performance model, but each is affected differently. An exception is that each system appears to indicate a drop in performance that begins around September 2017, reaches a minimum near January 2018 and then recovers. The effect is primarily seen in measured current but appears to also be present in measured voltage for CIGS-6. While other seasonal dips are observed, none are as pronounced or consistently affect all systems. As of this writing, recovery had yet to plateau. A clear explanation for this behavior also has yet to be uncovered, although it was observed that this period was particularly dry in Albuquerque.

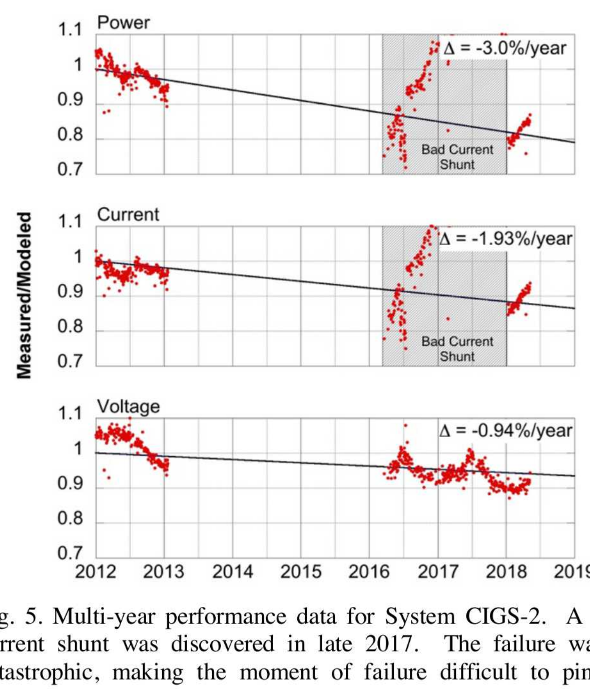

Fig. 5. Multi-year performance data for System CIGS-2. A failed current shunt was discovered in late 2017. The failure was not catastrophic, making the moment of failure difficult to pinpoint. Voltage measurements during this time were determined to be reliable.

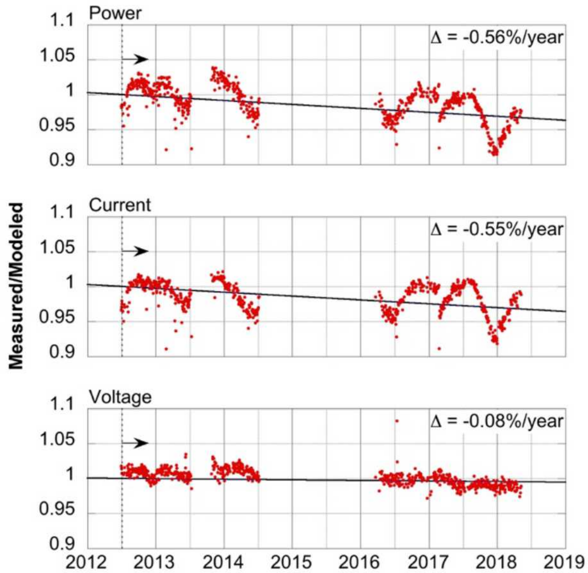

Fig. 6. Multiyear performance data for System CIGS-3. In contrast to flash test data, this system appears to have a slight year-over-year degradation in measured power. However, excluding the pronounced dip centered about January 2018 a seasonal analysis may still support the flash test results.

Unfortunately, due to the failed current transducer and paucity of data available for CIGS-2, little can be said about the seasonal performance of power or current. Voltage, however, appears to display a pronounced peak at the summer solstice and a softer valley at the winter solstice. This is consistent with the data presented in [3]. Here, it was observed that this module features a non-linear diode factor (Ref. 3, Fig. 4) that becomes greater in magnitude at low irradiance/low temperature. The current formulation of the SAPM does not account for this and leads to overprediction of voltage under these conditions, leading to an apparent dip in performance at the winter solstice.

CIGS-3 displays distinct peaks in current near the winter solstices and valleys near the summer solstices. Peaks are generally close to 1 while valleys are around 0.95, indicating good model prediction accuracy in the winter and around 5% overprediction in the summer. At this time, it is not known if this is the result of an improperly calibrated model parameter (temperature coefficient for Imp, for example) or an actual seasonal variation in performance that is not captured by the model. In contrast, seasonal variation in voltage is relatively low, indicating good prediction accuracy. Interestingly, the monitored system data implies a low year-over-year degradation in Pmp and Imp that is contrary to the flash test results, where no degradation was observed. This may in part be due to the deep valley in performance observed for all systems near the winter solstice of 2018. If this data is excluded, peaks and valleys in current appear to be consistent year-over-year.

CIGS-6 displays similar peaks and valleys in current centered about the solstices. As with CIGS-3, values near the winter solstice are close to 1, again indicating good model prediction accuracy. However, peaks occur during the summer solstice where ~ 3% underprediction is observed. Voltage also shows seasonality, with prediction accuracy generally being higher near the summer solstice and lower near the winter solstice.

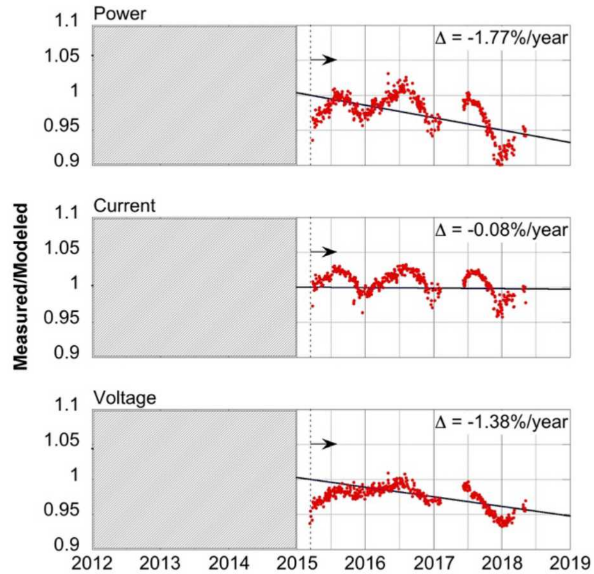

Fig. 7. Multiyear performance data for System CIGS-6. This system displays the most consistent seasonal variability of the three systems

A comparison of degradation rates determined from both flash testing and analysis of the monitored array data is given in Table IV. Results are generally comparable with a few exceptions, already noted. In particular, monitored system data implied degradation in current in CIGS-3 when none was observed in flash testing. Flash testing of CIGS-6 indicated degradation in current, whereas monitored system data indicated low degradation.

TABLE IV
COMPARISON OF RATE OF CHANGE DETERMINED FROM FLASH TESTING AND ANALYSIS OF ARRAY DATA

System	Power		Current		Voltage	
	Flash	Array	Flash	Array	Flash	Array
CIGS-2	-2.4%	-3.0%	-1.7%	-1.9%	-0.7%	-0.9%
CIGS-3	+0.3%	-0.6%	+0.4%	-0.6%	-0.1%	-0.1%
CIGS-6	-1.8%	-1.8%	-0.7%	-0.1%	-1.1%	-1.4%

V. SUMMARY

In this paper, we have characterized the stability and behavior of three grid-tied CIGS PV systems operating across multiple years. Stability was assessed using indoor STC flash measurements and analysis of monitored system data. Monitored system data was compared to model predictions using the Sandia Array Performance model, calibrated for each module type using data obtained from outdoor tracker testing.

From flash test data, one system was seen to continue degrading at a high rate of -2.4%/year, comparable to that determined in 2017. A second system was seen to have maintained performance with no observable degradation year over year. The last system, which showed no signs of degradation in 2017, showed a one-year drop in power of -5.7% power corresponding to a high year over year degradation rate of -1.8%. Both I_{mp} and V_{mp} were affected, as were series and shunt resistances.

Comparison between measured and modeled system performance data and flash test data indicated that the SAPM was effective at tracking performance degradation over time. In one case, analyzed system data indicated the possibility of degradation that was not apparent from STC flash test data. However, this data set might have been affected by anomalous weather conditions for that season. Further tracking of the system will be required to validate or refute this observation.

Seasonal variations were observed in measured system data compared to model predictions for all systems in this study. Each system displayed variability in predicted current. For two of the systems, model predictions matched measured current near the winter solstice. However, during the summer the model over-predicted in one case and under-predicted in the other. One system displayed seasonal variation in predicted voltage that is consistent with a known non-linearity in diode factor. A second system displayed seasonal variation in voltage that appeared to be consistent with variability in current. Voltage for the last system was easily predicted by the model and was seen to be stable year over year.

Future work on these systems will include continued monitoring to determine if each recovers fully from the anomalous dip in performance observed over the 2018 winter solstice, as well as investigation into measured weather data over this period for evidence of an anomalous environmental condition. Measured/modeled data will be further analyzed to determine if improvements to either the SAPM or calibration methods for it can be implemented.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy Solar Energy Technologies Office under Agreement 30288.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

REFERENCES

[1] M. A. Green, et. al., "Solar cell efficiency tables (Version 49), *Progress in Photovoltaics: Research and Applications,* 25: pp. 3-13, 2017.

[2] M. Theelen and F. Daume, "Stability of Cu(In,Ga)Se2 solar cells: A literature review," *Solar Energy*, 133, pp 586-627, 2016.

[3] B. H. King, et. al., "Degradation Assessment of Fielded CIGS Photovoltaic Arrays," *44th IEEE Photovoltaic Specialists Conference*, Washington, DC, 2017.

[4] D. L. King, W. E. Boyson, J. A. Kratochvil, "Photovoltaic Array Performance Model,", Sandia National Laboratories, SAND2004-3535, 2004.

[5] K. A. Klise and J. S. Stein, "Automated Performance Monitoring for PV Systems Using PECOS," in *43rd IEEE Photovoltaic Specialists Conference*, Portland, OR, 2016.

[6] IEC 61215-1-4:2016, "Terrestrial photovoltaic (PV) modules – Design qualifications and type approval – Part 1-4: Special requirements for testing fo thin-film $Cu(In,Ga)(S,Se)_2$ based photovoltaic (PV) modules."

[7] B. H. King, et. al., "Outdoor Test and Analysis Procedures for Generating Coefficients for the Sandia Array Performance Model," in *43rd IEEE Photovoltaic Specialists Conference*, Portland, OR, 2016.

[8] B. H. King, C. W. Hansen, D. Riley, C. D. Robinson and L. Pratt, "Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM)," Sandia National Laboratories, SAND2016-5284, 2016.

[9] B. King, "CIGS Performance Analysis: Alternative Method to Fit the Sandia Array Performance Model," 5th PV Performance Modeling Workshop, San Jose CA, 2016.

[10] R. Singh, et. al., "Analyses of Measurement Parameters for Laboratory Characterization of the Operating Temperature Coefficients of CI(G)S PV Modules," *43rd IEEE Photovoltaic Specialists Conference*, Portland, OR, 2016

[11] M. J. Reno and C. Hansen, "Identification of Periods of Clear Sky Irradiance in Time Series of GHI Measurements," *Renewable Energy*, 2016

[12] PV_LIB Toolbox, Version 1.32.

[13] IEC 61724-1:2017, "Photovoltaic system performance – Part 1: Monitoring."